

# USING BIOECONOMIC MODELS TO MAXIMIZE BENEFITS FROM VERTEBRATE PEST CONTROL: LAMB PREDATION BY FERAL PIGS

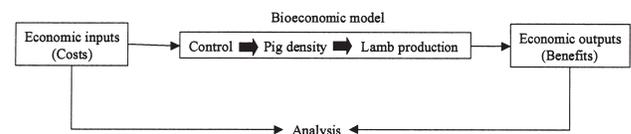
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**Abstract:** The question “When should investment in pest control stop?” either explicitly or implicitly underpins decisions concerning pest control made at every level of enterprise or government, regardless of whether these decisions are tactical or strategic. Bioeconomic modeling provides a quantitative framework for considering the benefits and costs of alternative pest control strategies. In this case study, we develop 3 bioeconomic models that examine strategies based on helicopter shooting and 1080 poisoning, for reducing feral pig (*Sus scrofa*) predation of newborn lambs in wool-growing enterprises located in Australia’s rangelands. In the first model, marginal analysis indicated that helicopter shooting was more profitable than 1080 poisoning when pasture biomass was above 220 kg·ha<sup>-1</sup>, and was most profitable when feral pig density was reduced to 1.5·km<sup>-2</sup>. Below pasture biomass of 220 kg·ha<sup>-1</sup>, 1080 poisoning became more profitable than helicopter shooting. The second model added logistic population growth for pigs so that control could be simulated through time. While the net benefit from helicopter shooting was still maximized when applied annually, and the profitability of 1080 poisoning was still dependent on pasture biomass, the return on investment from both strategies increased markedly. While the third model, which added stochastic environmental variation, further increased the profitability of control, it also introduced uncertainty to the net benefits realized. For helicopter shooting, annual application remained most profitable.

**Key words:** benefit/cost analysis, bioeconomic modeling, feral pigs, lamb predation, marginal analysis, *Sus scrofa*.

The management of wildlife as pests involves making choices that determine how much pest control will cost, and what benefit it will deliver. In order to make these choices defensible, the effect that alternate courses of action have on how the costs and benefits of pest control accrue should ideally be understood. To understand how benefits and costs vary among different pest management strategies, the biological and management components of a pest/resource system must be linked so that its economic inputs and outputs can be estimated and compared. Clark (1976, 1990) coined the term “bioeconomics” to describe the economic analysis of biological systems, and described a conceptual and mathematical framework that links the dynamics of biological populations with the economic imperatives that drive their management. The emphasis Clark (1990) placed on the use of analytical models to predict the effect of management on system behavior, has more recently been extended to include dynamic programming and simulation/optimization approaches that are useful when system behavior is stochastic or uncertain (Williams 1989, Hilborn and Mangel 1997). However, regardless of how they are actually implemented, the principles of bioeconomics provide a potentially powerful approach to the analysis of pest management systems. Given this potential, it is surprising how few examples of bioeconomic analysis have been reported for wildlife pest management (Hone 1994).

In this paper we describe 3 bioeconomic analyses of feral pig (*Sus scrofa*) management to enhance lamb production in Australia’s eastern rangelands. The analyses described are based on models that use interaction between control, pig density and lamb production to



**Fig. 1.** The general structure of the models developed in this paper. The bioeconomic model, which can have varying levels of complexity, is used to link economic inputs to the management system (in this case the costs of feral pig control), and consequent economic outputs (in this case the benefits of pig control). These economic inputs and outputs are analyzed to identify pest control strategies that produce some optimal outcome. For feral pig control to increase lamb production, analyses would seek the control strategy that maximized the return on investment (i.e., profit).

contrast the economic inputs to pig management (the cost of controlling feral pigs), with its economic outputs (the value of benefits that accrue from control through improved lamb production) (Fig. 1). Our aim in describing these analyses is not to provide an exhaustive coverage of the ways in which bioeconomic modeling can be applied in pest management, or to provide a particularly comprehensive summary of management options for feral pigs. Rather, we hope to make the point that there are a range of approaches available for assessing the economic performance of alternative pest management strategies.

## FERAL PIGS AND LAMB PRODUCTION IN AUSTRALIA’S EASTERN RANGELANDS

Feral pigs are widespread and abundant in the semi-arid rangelands of eastern Australia. Sheep farmers

in the rangelands spend a great deal of time and money controlling feral pigs to limit the extent to which they prey on newborn lambs (Choquenot et al. 1996). Feral pigs have also been recognized as an economically important predator of lambs and kid goats in the southern United States (Beach 1993). Lamb production is critical to the viability of wool-growing enterprises in the rangelands because most flocks are self-replacing, farmers rely on a broad genetic flock-base to select for commercially important wool quality traits, and sale of excess lambs is an important source of cash income (Alexander 1984). The significance of lamb predation by feral pigs was first recognized by Moule (1954). Subsequent research by Plant et al. (1978), Pavlov et al. (1981), Pavlov and Hone (1982) and Choquenot et al. (1997) has progressively refined estimates of the extent to which feral pigs prey on lambs, but has not attempted a formal economic analysis of the problem. Where feral pigs are considered a significant impediment to the economic viability of rangelands wool-growing enterprises, they are trapped, poisoned, shot from helicopters, or hunted from the ground (Choquenot et al. 1996). Of all of these techniques, helicopter shooting and poisoning are the most commonly used. Tisdell (1982) developed conceptual models of how the cost control using these techniques might vary in relation to their benefits, but did not undertake a formal analysis of these models.

**COMPONENTS OF THE BIOECONOMIC MODELS**  
**Feral Pig Population Dynamics**

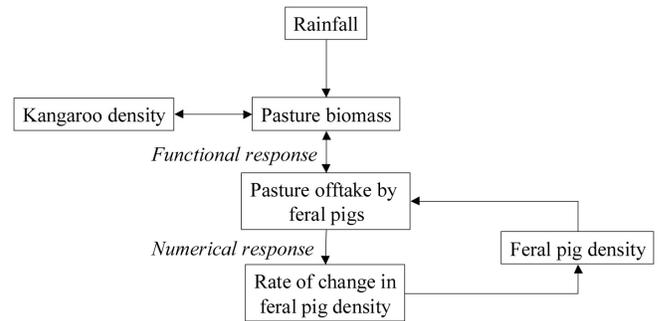
The feature of the rangelands that has most influence on the efforts of sheep farmers to manage their wool-growing enterprises is the intrinsic uncertainty of rainfall. The long-term seasonal rainfall statistics summarized in Table 1 indicate that the predictability among seasons and among years is very low. While this has implications for many decisions farmers have to make concerning stock management, it also has a profound influence on how the density of feral pigs varies through time.

Giles (1980) conducted a broad study of feral pig population dynamics in the rangelands of western NSW, based on extensive mark-recapture studies and

**Table 1. Annual and seasonal average rainfall (mm) at Wanaarring on the Paroo River in northwestern NSW, and associated standard deviations (SD) and coefficients of variation (CV). Seasonal rainfall is the mean for 3 months for the period 1926-91.**

	Season				Year
	Summer (Dec-Feb)	Autumn (Mar-May)	Winter (Jun-Aug)	Spring (Sep-Nov)	
Rainfall (mm)	63	52	53	57	193
SD	55	55	25	44	94
CV	87%	106%	45%	77%	49%

autopsy of large shot samples. He concluded that the variability in feral pig density in the rangelands was due to stochastic variation in prevailing seasonal conditions, rate of change in pig density being determined largely by the effect that availability of dietary protein had on prevailing demographic rates. Dietary studies demonstrated that protein ingested by feral pigs came mostly from fresh green legumes, grasses and forbs. When adequate green feed was not available, pigs consumed mostly roots and tubers which were rich in digestible carbohydrates but contained little protein. Choquenot (1998) measured simultaneous variation in pasture biomass and feral pig density on 6 sites in the rangelands to more formally evaluate interaction between pasture biomass and rate of change in feral pig density. He found a strong systematic relationship between pasture biomass and the instantaneous rate of change in feral pig density (*r*). Choquenot (1998) developed a simulation model of interaction between feral pigs and pasture biomass based on this relationship, that can be modified to directly link pasture intake and rate of change in feral pig density (Fig. 2). The model is based on a hypothetical model of vegetation-herbivore interaction described by Caughley (1976) and later estimated for red kangaroos (*Macropus rufus*) interacting with pasture in the rangelands (Caughley 1987).



**Fig. 2. A schematic representation of the model use to predict variation in feral pig density in the bioeconomic models of feral pig control.**

In the model variation in ungrazed pasture biomass (*PB*) was predicted by a function that accounted for empirically estimated effects of variation in rainfall and prevailing pasture biomass on pasture growth and die-back by:

$$\Delta PB = -55.12 - 0.01535 PB - 0.00056 PB^2 + 3.946R \quad (1)$$

where  $\Delta PB$  is the pasture growth increment over 3 months in the absence of grazing, *PB* is pasture biomass at the start of that period and *R* is the rainfall in mm over the 3 months (Caughley 1987). Because pasture growth in the rangelands is not seasonal, equation 1 does not include a term for temperature effects. The pasture growth increment was taken as a random draw from a normal distribution with mean equal to the

solution of equation 1 and a standard deviation of 52 kg·ha<sup>-1</sup>, equivalent to the variation in pasture growth not accounted for by rainfall and standing biomass (Robertson 1987).

Feral pigs were added to the model using a functional response to predict variation in their quarterly rate of pasture intake ( $IR$ ) with changes in pasture biomass (Choquenot 1998), and their numerical response which predicted their instantaneous quarterly rate of change in density ( $r$ ) as a function of pasture intake. Pigs were assumed to average 35 kg in bodyweight, which corresponds to functional and numerical responses described by:

$$IR = 75 \left[ 1 - e^{-(PB-92)/302} \right] \quad (2)$$

and

$$r = -0.193 + (IR/0.0054) \quad (3)$$

Equation 3 indicates that in the absence of pasture (i.e.,  $IR$  falls to 0), feral pig populations will decline at an instantaneous rate of -0.193 quarter<sup>-1</sup>.

Red kangaroos (also assumed to average 35 kg in bodyweight) were used in the model as a surrogate for other herbivores in the grazing system, their functional and numerical responses being taken from Short (1987) and Bayliss (1987) respectively, who estimated them as:

$$IR = 86 \left( 1 - e^{-PB/34} \right) \quad (4)$$

and

$$r_H = -1.6 + 2 \left( 1 - e^{-0.007PB} \right) \quad (5)$$

The model was used to simulate variation in pasture biomass and feral pig density by driving pasture growth (equation 1) with quarterly rainfall drawn at random from normal distributions with averages and standard deviations equal to those in Table 1. Rates of change in feral pig and kangaroo density were projected from pasture intake rate and standing pasture biomass respectively at the start of each quarter, and changes in their abundance and offtake of pasture accounted weekly. Fig. 3 shows variation in pasture biomass and feral pig density for a typical 50-year run of the resultant model.

### Lamb Predation Dynamics

Choquenot et al. (1997) conducted 2 large-scale experiments to quantify the effects that predation by feral pigs had on lamb production. The primary aim of these experiments was to estimate the relationship between feral pig density and lamb predation rate. In the first experiment, regression analysis was used to partition variation in an index of lamb loss by free-ranging sheep (%LL) into that related to feral pig density ( $P$ ) and that due to other sources. The form of the relationship was:

$$\%LL = 6.34 \left( 1 - e^{-P/2.26} \right) \quad (6)$$

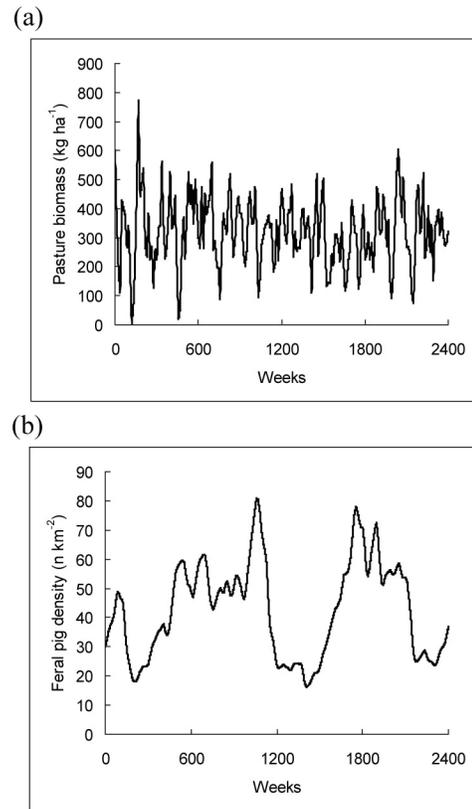


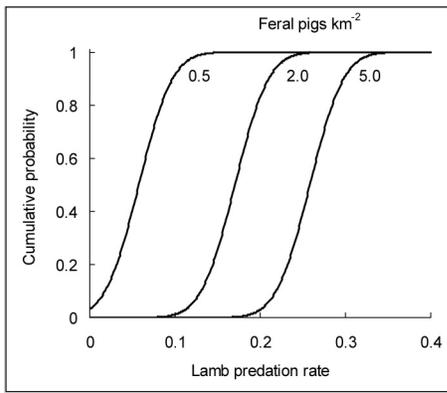
Fig. 3. Variation in (a) pasture biomass and (b) feral pig density over 50 years, predicted by a mechanistic model that simulates interaction between pigs and pasture.

which explained 78% of the variation in the index, leaving residual variation equivalent to a coefficient of variation in lamb predation rate of CV = 21.72%.

In the second experiment, predation rate was estimated directly by contrasting the lamb rearing performance of pregnant ewes that were randomly assigned to electric-fenced paddocks to which pigs had no access (protected), or conventionally fenced paddocks which provided no impediment to pigs (unprotected). Three pairs of paddocks were used in the experiment, 1 at a pig density of 0.4·km<sup>-2</sup>, 1 at a density of 2.4·km<sup>-2</sup>, and 1 at a density of 5.8·km<sup>-2</sup>. Lamb predation rate, estimated from the difference between protected and unprotected paddocks in the proportion of lambs born that were weaned, was positively correlated with feral pig density. The maximum estimated rate of predation (the maximum proportion of lambs available that were eaten, 0.29) was substituted for the maximum index of lamb loss in equation 6, to modify the relationship to predict lamb predation rate over the lambing season ( $PR$ ) directly from pig density:

$$PR = 0.29 \left( 1 - e^{-P/2.26} \right) \quad (7)$$

The CV for equation 1 was also re-scaled using the results from the second experiment to estimate a standard deviation equivalent to variation in lamb loss



**Fig. 4. Cumulative probability of lamb predation rate exceeding specified levels, as a function of feral pig density, estimated from equation 8. The curves for the 3 feral pig densities shown correspond to average predation rates of 0.058 at 0.5 feral pigs·km<sup>-2</sup>, 0.170 at 2.0 feral pigs·km<sup>-2</sup>, and 0.258 at 5.0 feral pigs·km<sup>-2</sup> (Choquenot et al. 1997).**

that was unrelated to feral pig density ( $\sigma = 0.031$ ). Attaching this standard deviation to average predation rate as a function of feral pig density (calculated from equation 2), allows distributions describing the normally-distributed probability of incurring different predation rates to be estimated at given feral pig density (Fig. 4) from:

$$f(PR) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\left[\frac{(PR-\mu)^2}{2\sigma^2}\right]} \quad (8)$$

**Controlling Feral Pigs: Helicopter Shooting**

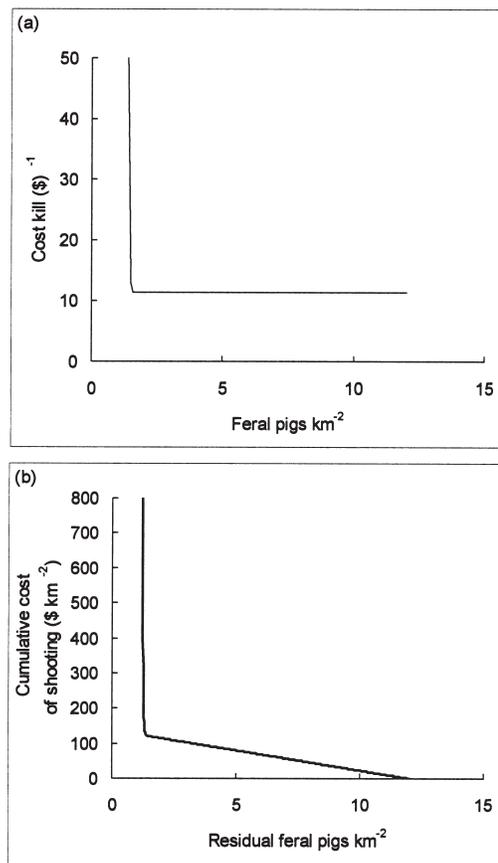
From a bioeconomic perspective, the most important aspects of the different techniques available to control pests are how much they cost and what reduction in pest density they achieve. Interdependent variation in these 2 characteristics determines the relative cost-effectiveness of a given control technique (Hone 1994).

The typically flat terrain, and sparse tree cover that predominates in the rangelands is highly conducive to shooting from helicopters (Choquenot et al. 1996). Unlike techniques requiring pigs to consume bait, helicopter shooting is not affected by seasonal conditions. The technique also allows control to extend into swampy country where feral pigs can otherwise be difficult to access, and because it is target-specific, helicopter shooting does not require stock to be removed from control areas. Smaller helicopters are generally sufficient for shooting under rangelands conditions, constraining the cost of a control program. Choquenot et al. (1999) contrasted quantitative evaluations of helicopter shooting for feral pig control in 3 parts of Australia. Here we will use the data collected for a shooting exer-

cise on the Mary River originally described by Hone (1990). Choquenot et al. (1999) related estimates of the time taken to kill each pig ( $Hrs\ kill^{-1}$ ;  $HrsKill$ ) at this site to changes in pig density (pigs km<sup>-2</sup>;  $P$ ) using the model:

$$HrsKill = 0.02 + e^{-(P-1.338)32.886} \quad (9)$$

Equation 9 can be used to estimate how cost·kill<sup>-1</sup> for helicopter shooting varies with prevailing feral pig density by multiplying predicted  $HrsKill$  by the time-dependent costs of helicopter shooting (fueled helicopter charter and labor), and adding the fixed cost of each kill (ammunition) (Fig. 5a, Table 2). The cost-effectiveness of helicopter shooting can then be calculated by accounting the cumulative costs of control as feral pig density is progressively reduced Fig. 5b. Cumulative costs increase linearly until densities are reached where the cost·kill<sup>-1</sup> increases dramatically (1.3 pigs·km<sup>-2</sup> according to equation 9). It is important to note that because costs accumulate linearly at pig densities below



**Fig. 5. The relationship between (a) cost·kill<sup>-1</sup> and feral pigs·m<sup>-2</sup>, and (b) cumulative costs and residual feral pig density, predicted from a model of helicopter shooting for the Mary River (Choquenot et al. 1999).**

**Table 2. Nominal costs for the components of helicopter shooting programs for feral pigs (Choquenot et al. 1999).**

Component	Unit-hour <sup>1</sup>	Cost (A\$.Unit <sup>1</sup> )
Fueled helicopter charter	1	\$300
Shooter	1	\$20
Ammunition (rounds-pig <sup>-1</sup> )	4	\$1

this level, they provide no guidance to the farmer as to what the current density of feral pigs might be. As such, if a farmer curtails shooting before cost·kill<sup>-1</sup> begins to increase dramatically, they will not know whether the residual density of feral pigs is 5 or 50·km<sup>-2</sup>.

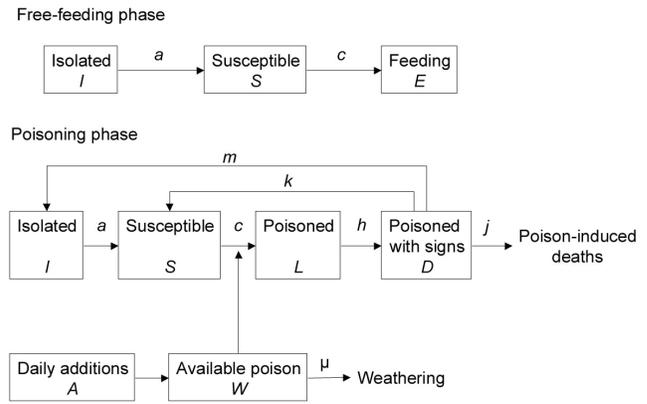
### Controlling Feral Pigs: 1080 Poisoning

Poisoning is a widely employed method of feral pig control in the rangelands. A poisoning operation usually has 2 parts; a free-feeding phase where non-poisoned bait (usually grain or commercial stock-feed pellets) is distributed as trails through the pest control area, and a poisoning phase where the non-poisoned bait being consumed at the end of the free-feeding phase is replaced with poisoned bait. The free-feeding phase serves 3 functions; (1) it lets farmers know whether there is sufficient bait-take to warrant a poisoning phase, (2) it maximizes the number of feral pigs that are consuming bait before poison is distributed, and (3) it is used to trail pigs into stock-proof enclosures in which the poisoned bait is usually distributed (Choquenot et al. 1996). The free-feeding phase generally lasts from 3 to 7 days. When poisoning follows free-feeding, it entails one-time distribution of an acute poison, usually 1080 (sodium monofluoroacetate).

Hone (1992) described a compartmental model of feral pig poisoning estimated from data collected during a poisoning program that used warfarin, which is a chronic feral pig poison. The model described free-feeding and poisoning as separate phases (Fig. 6). A series of linked differential equations were used to describe these phases:

<i>Free feed</i>	<i>Poisoning</i>	
$dI/dt = T - aI$	$dI/dt = T + mD - aI$	
$dS/dt = (1 - T) + aI - cS$	$dS/dt = aI + kD - cS$	
$dE/dt = cS$	$dL/dt = cS - hL$	(10)
	$dD/dt = hL - jD - kD - mD$	
	$dW/dt = A - (P + \mu)W$	

where  $a$ ,  $c$ ,  $k$ ,  $h$ ,  $j$ ,  $m$  and  $\mu$  are rates of transfer per unit time,  $T$  is a constant, and  $P$  is the prevailing density of the population. While Hone (1992) assumed that no portion of the free-fed or poisoned population was

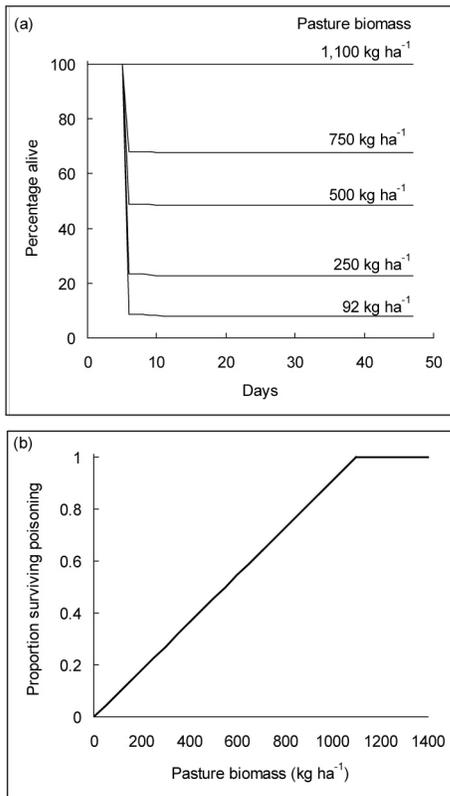


**Fig. 6. A schematic compartmental model of the two phases of a feral pig poisoning program. Symbols in boxes represent densities of feral pigs that are isolated from bait trails ( $I$ ), susceptible to bait consumption ( $S$ ), feeding on nonpoisoned bait ( $E$ ), feeding on poisoned bait ( $L$ ) and showing signs of poisoning ( $D$ ), and quantities of poisoned bait currently available to feral pigs ( $W$ ), and being added to that available ( $A$ ). Arrows indicate the rate of transfer between classes of feral pigs or bait, and associated letters represent rates of transfer per unit time (Hone 1994).**

isolated from bait, here we have included a component of the population ( $I$ ) that can be behaviorally isolated from taking bait. Choquenot et al. (1990, 1993) found that some pigs would not consume bait despite commonly encountering bait trails. We assume that pigs not consuming bait by the end of the free-feeding phase of the program are behaviorally isolated from bait and will not be susceptible to poisoning. This component of the population is assumed to represent a proportion of the population ( $T$ ) that is constant over the life of a poisoning program (i.e.,  $a = 0$ ). Variation in  $T$  between poisoning programs was dependent on prevailing pasture biomass. Choquenot & Lukins (1996) evaluated the effect of prevailing biomass and feral pig density on bait consumption in the rangelands. They concluded that while most pigs would consume bait when pasture biomass was below 92 kg·ha<sup>-1</sup> (the biomass below which pigs are unable to graze pasture), few pigs would consume bait when pasture biomass exceeded 1,100 kg·ha<sup>-1</sup>. The effect that varying pasture biomass ( $PB$ ) has on the effectiveness of trapping and poisoning programs was built into the compartmental model described above by setting  $T$  to 1 or 0, when pasture biomass was alternatively below 92 kg·ha<sup>-1</sup> or above 1,100 kg·ha<sup>-1</sup>, and substituting:

$$T = [109 + (-0.099PB)]/100 \quad (11)$$

when pasture biomass is between those levels. All pigs not behaviorally isolated from bait ( $1 - T$ ) would consume bait and could be poisoned ( $S$ ), changing from being potential to actual consumers of either non-poisoned or poisoned bait ( $E$  and  $L$ , respectively) at a daily



**Fig. 7.** Variation in (a) the proportion of feral pigs surviving 1080 poisoning operations as a function of prevailing pasture biomass, and (b) the estimated percentage of feral pigs surviving 1080 poisoning programs as a function of pasture biomass. Both relationships were estimated from the compartmental model of poisoning described in the text.

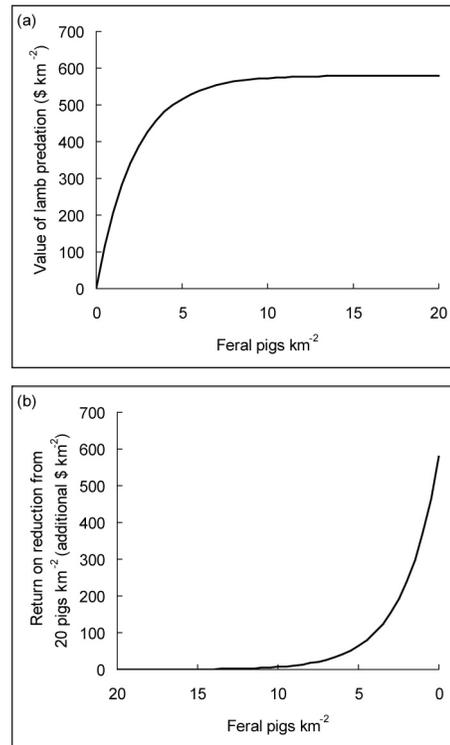
per capita rate of  $c = 0.56$  (Hone 1992, 1994). Assuming that poison is always available to pigs ( $W + A - \mu$  exceeds consumption), all pigs in class  $E$  at the end of the free-feeding phase will move to class  $L$  at the commencement of poisoning. Hone (1994) estimated that the average time to development of signs of warfarin poisoning was 3 days, so that  $b$  was  $0.333 \cdot \text{day}^{-1}$ . Following the onset of symptoms, 92% of pigs died, with an average time to death of 7 days (McIlroy et al. 1989). In contrast to warfarin’s chronic mode of action, 1080 kills feral pigs in, at most, a day (Choquenot et al. 1996). Hence, assuming that a 1080 poisoning program also achieves a 92% kill,  $b$  for a 1080 program will be 1 and  $j$  will be  $0.92 \cdot \text{day}^{-1}$ . However, because 1080’s acute mode of action is much more likely to induce bait shyness in feral pigs, most of the 8% of poisoned pigs that survive will probably become behaviorally isolated for at least some time following a 1080 poisoning program. Hence,  $m$  may be as high as 0.08, and  $k$  as low as 0.

The implication of variation in  $T$  with prevailing pasture biomass is that fewer feral pigs will consume bait when pasture is plentiful, reducing the effectiveness of poisoning as pasture biomass increases toward  $1,100 \cdot \text{kg ha}^{-1}$ . To quantify this influence, the compart-

mental model of 1080 poisoning was used to project the progress of operations, as pasture biomass was progressively varied (Fig. 7a). This analysis implies that the proportion of a feral pig population surviving 1080 poisoning programs ( $S_{1080}$ ) increases with prevailing pasture biomass ( $PB$ ) between 0 and  $1,100 \text{ kg} \cdot \text{ha}^{-1}$  (Fig. 7b). The relationship between survival and pasture biomass is described by:

$$S_{1080} = 0.000907 PB \quad (12)$$

In contrast to helicopter shooting, farmers cannot choose to halt investment in a 1080 poisoning at any point in time. When contemplating feral pig poisoning, farmers can elect not to proceed at all, or not to extend the free-feeding phase into a poisoning phase. In the first case they will incur no expense and achieve no reduction in feral pig density, while in the second case they will incur the cost of free-feeding and still achieve no reduction in feral pig density. The decision not to proceed with free feeding will generally be made on the basis of how much pasture is available to pigs, because of the influence this has on the number of pigs likely to take bait and hence be susceptible to poisoning. The decision not to extend free-feeding into a poisoning phase will generally be made if bait-take is poor as few pigs will be killed. Assuming poisoning follows free-



**Fig. 8.** Relationships predicting (a) the value of lambs eaten by feral pigs as a function of feral pig density, and (b) the estimated return from reducing feral pigs to specified densities from an initial density  $20 \cdot \text{km}^{-2}$ . Both relationships assume that maximum annual production of lambs is  $200 \cdot \text{km}^{-2}$ , and the replacement value of each lamb eaten is A\$10.

feeding, farmers will incur the expense of both phases of an operation (Table 3), but the effectiveness of the program will depend on prevailing pasture biomass.

**Table 3. Nominal costs for the components of feral pig poisoning programs employing either 1080 or warfarin. The costs given are approximations, informed where possible from estimates given in Choquenot et al. (1996).**

Component	Unit·km <sup>-2</sup> ·day <sup>-1</sup>	Cost (A\$·unit <sup>-1</sup> )
Transport (free-feeding or poisoning)	1 km	\$1
Labor (free-feeding)	0.5 hr	\$10
Additional labor (poisoning)	0.1 hr	\$10
Bait (free-feeding or poisoning)	30 kg max. <sup>2</sup>	\$0.1
Bait station materials	0.25	\$3 <sup>1</sup>
Poison	Unit·kg bait <sup>-1</sup> ·day <sup>-1</sup>	
Additional cost of 1080 (poisoning)	0.5 gm	\$0.5 <sup>3</sup>

<sup>1</sup> Assuming the cost of a single bait station (A\$30) is discounted across 10 poisoning programs

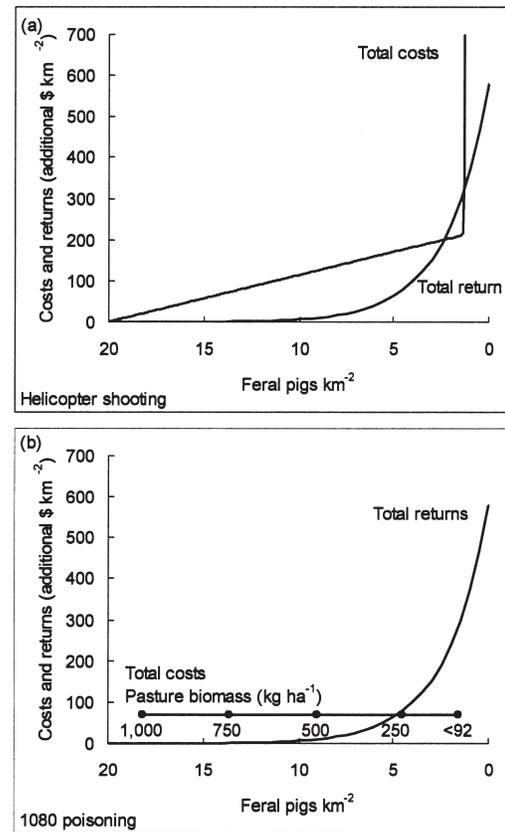
<sup>2</sup> The amount needed to replace all bait trails being consumed in one km<sup>2</sup> at the conclusion of the free-feeding phase of the program

<sup>3</sup> Cost of the prepared toxin and associated materials necessary to conduct a poisoning program (e.g., bait bags, warning signs)

## BIOECONOMIC MODELS

### Benefit/Cost Analysis

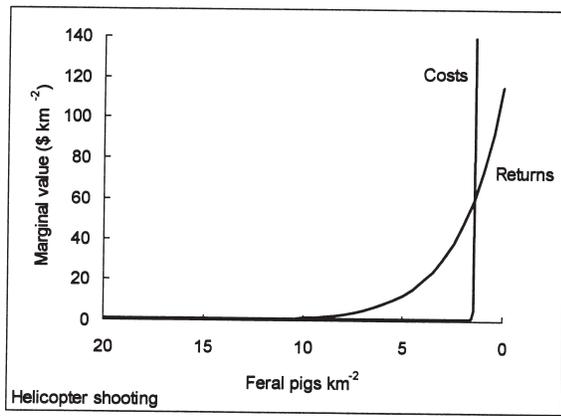
Perhaps the most straightforward bioeconomic model that can be developed from these components is a direct comparison of the benefits and costs of feral pig control using helicopter shooting or 1080 poisoning. The net benefit of feral pig control relative to no control will be the value of additional lambs produced due to control, less the cost of the control undertaken. The number of additional lambs produced will be the difference in lamb yield with and without feral pig control. For example, if lambing occurs over an 8-week period each spring with an average weekly production of 25 viable lambs·km<sup>-2</sup>, the yield of lambs in the absence of pigs would be 200 lambs·km<sup>-2</sup> for the season. If the replacement cost of these lambs was A\$10, the value of lamb production to the farmer each spring would be A\$2,000·km<sup>-2</sup>. The number of lambs eaten by feral pigs as a function of feral pig density can be estimated from equation 7, and valued by multiplying this number by A\$10 (Fig. 8a). When feral pig density reaches 20·km<sup>-2</sup>, the value of lambs they consume is A\$580·km<sup>-2</sup>. If this is taken as a good estimate of the cost a farmer incurs by having uncontrolled feral pig densities on their property, the economic return from reducing pigs to densities below 20 km<sup>-2</sup> will be the difference between A\$580 and the value of predation at the reduced density (Fig. 8b). Little benefit is achieved until pig densities are



**Fig. 9. Costs and returns of (a) helicopter shooting and (b) 1080 poisoning for feral pig control to increase lamb production. Total costs are those required to reduce pig density from 20·km<sup>-2</sup> to the densities specified on the x-axis, and returns are the value of increased lamb production, assuming that maximum annual production is 200·km<sup>-2</sup>, and the replacement value of each lamb eaten is A\$10. For 1080 poisoning, costs are independent of feral pig density, but effectiveness (the density to which poisoning reduces the pig population) is determined by prevailing pasture biomass.**

reduced below about 10·km<sup>-2</sup>, beyond which the return on control increases rapidly. Benefits accruing from pig control increase in an accelerating fashion because the underlying relationship between pig density and lamb predation rates is asymptotic (equation 7).

To determine whether the economic returns realized from reduced feral pig density will increase the profitability of the wool growing enterprise, they must be compared with the costs of pig control necessary to achieve them. The cumulative cost of reducing feral pig density to progressively lower densities by helicopter shooting can be estimated from equation 9, and the density to which feral pigs can be reduced for a set expenditure on 1080 poisoning can be estimated from the compartmental model described by equations 10. The cumulative costs of helicopter shooting and 1080 poisoning are plotted against the total returns from control in Fig. 9a and Fig. 9b. The cost of helicopter shooting is greater than the returns it yields down to a feral pig



**Fig. 10.** Marginal returns and costs of helicopter shooting for feral pig control to increase lamb production, taken from the total benefit and cost curves shown in Fig 11(a). Costs are those required to reduce pig density from 20·km<sup>-2</sup> to the densities specified on the x-axis, and returns are the value of increased lamb production, assuming that maximum annual production is 200·km<sup>-2</sup>, and the replacement value of each lamb eaten is A\$10.

density of 2.2·km<sup>-2</sup>, and again below a density of 1.5·km<sup>-2</sup>. As such, helicopter shooting was only profitable if it continued until feral pig density declined below 2.2·km<sup>-2</sup>, but halted before feral pig density fell below 1.5·km<sup>-2</sup>. Unlike helicopter shooting, the effectiveness of 1080 poisoning is influence by pasture availability. As pasture biomass increases above 92 kg·ha<sup>-1</sup>, the effectiveness of 1080 poisoning declines despite costs remaining constant. The consequence of this decline is that 1080 poisoning only reduced feral pig density to levels where returns exceeded its costs when pasture biomass was less than about 260 kg·ha<sup>-1</sup>.

While Fig. 9a and Fig. 9b indicate that helicopter shooting was profitable over a narrow range of feral pig densities and 1080 poisoning when pasture biomass was low, it will be of interest to farmers to know more precisely when the profit derived from each control technique was maximized. The level of feral pig control that achieves the highest return on investment can be identified by contrasting the marginal change in the costs and returns of control as the level of control is increased (Clark 1990). The marginal curves corresponding to the total cost and return curves for helicopter shooting intersect at a feral pig density of 1.5·km<sup>-2</sup>, indicating that reducing feral pig density to this level maximizes the profitability of helicopter shooting (Fig 10). At a density of 1.5 feral pigs·km<sup>-2</sup>, the ratio of benefits to costs for helicopter shooting is 1.38, indicating a profit of 38 cents on every dollar invested in shooting.

The cost of 1080 poisoning operations was constant, precluding marginal analysis of their relative profitability (the marginal change in costs would be 0).

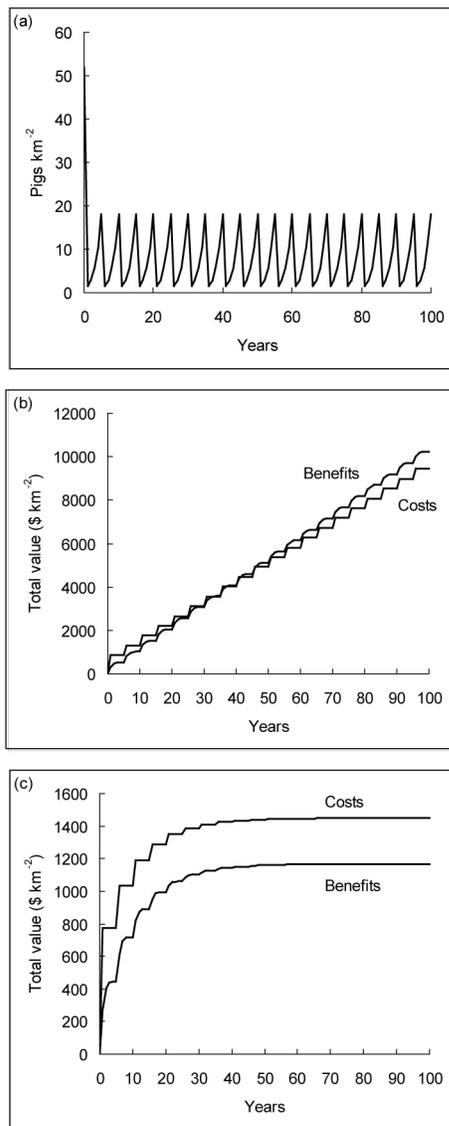
However, because the potential return from reducing feral pigs to progressively lower densities continues to increase until pig density reaches 0, the profitability of poisoning programs will simply reflect their effectiveness. Because the effectiveness of 1080 poisoning operations increases as pasture biomass declines toward 92 kg·ha<sup>-1</sup>, their profitability will also increase. The ratio of benefits to costs accruing from 1080 poisoning when pasture biomass is less than 92 kg·ha<sup>-1</sup> is 4.42, indicating a profit of A\$3.42 on every dollar invested in poisoning. The reduction in the profitability of 1080 poisoning as pasture biomass increases above 92 kg·ha<sup>-1</sup> means that at some point its profits will equate with those of helicopter shooting. Iteration of the costs and benefits of poisoning as pasture biomass is increased indicates that the profit from 1080 poisoning declines below that of helicopter shooting when pasture biomass exceeds about 220 kg·ha<sup>-1</sup>. The decline in the effectiveness of 1080 poisoning suggests that when pasture biomass is above this level, farmers should use helicopter shooting to control feral pigs, but should not attempt to reduce their density below 1.5·km<sup>-2</sup>. When pasture biomass is below that level, farmers should use 1080 poisoning for feral pig control.

### Benefit/Cost Analysis Incorporating Time

The analysis described above assumes that farmers wishing to profit from feral pig control are always dealing with the problem of reducing high pig densities to levels where their effect on lamb predation is reduced. However, having out-laid the cash to reduce feral pigs to low densities, it may be foolish to allow them to recover to high densities before undertaking additional control. In order to take account of the effect that time has on the accrual of benefits and costs in pest control, the dynamics that drive changes in pest abundance must be explicitly considered in benefit/cost analyses (Hone 1994). A simple model that can be used to predict changes in the abundance of a pest population from its prevailing density (P) is the logistic:

$$\frac{dP}{dt} = P \cdot r_m \left( 1 - \frac{P}{K} \right) \quad (13)$$

where  $r_m$  is the maximum instantaneous rate of change in pest density and  $K$  is the density of the pest population at carrying capacity. The logistic has been used to predict feral pig population dynamics in epidemiological models (Pech and Hone 1988, Pech and McIlroy 1990). To estimate the logistic for feral pigs in the rangelands we used an estimate of  $r_m$  from Choquenot (1998) (0.69), and estimated  $K$  by projecting the equilibrium pig density from the interactive model described in equations 1 to 5, after stochastic variation in rainfall and pasture growth were omitted (52·km<sup>-2</sup>). Mechanistic models like the interactive allow the response of pest populations to control to be predicted more accurately than single-species models such as the logistic (Caugh-



**Fig. 11.** Predicted changes in (a) feral pig density, (b) the total value of benefits and costs of control, and (c) the present value of benefits and costs of control, for a control strategy in which pigs are reduced by helicopter shooting from their carrying capacity (52 pigs·km<sup>-2</sup>) in year 1, and then to 1.5·km<sup>-2</sup> every 5 years thereafter. The discount rate used to convert total values to present values is 10% per annum.

ley and Gunn 1996). However, because it is rare to have sufficient data to estimate mechanistic models, we will use the logistic model of pig population dynamics to discuss the general principles involved in including time in benefit costs analysis. In the next section we will re-introduce the interactive model as we add the complexity of environmental stochasticity to these analyses.

Fig. 11a shows changes in a controlled feral pig population over 100 years predicted by the logistic model, with initial reduction from carrying capacity by

helicopter shooting in year 1, and subsequent shooting programs carried out every 5 years thereafter. Each shooting operation reduces feral pig density to 1.5·km<sup>-2</sup>, which was the limit to profitable application of the technique identified in the previous analysis. Adopting this strategy for helicopter shooting accumulates costs over the 100 years considered in the model, and yields benefits through improved lamb production. However, because the costs and benefits of control accumulate at different rates, they must be aggregated through time if they are to be contrasted in a meaningful way. Fig. 11b shows the cumulative change in the value of costs and benefits for the helicopter shooting strategy described over the 100 years it was modeled. The cumulative benefits of control are initially lower than its cumulative costs because of the high cost associated with the initial reduction of feral pigs from carrying capacity. However, at around 40 years, the value of the accumulated benefits of control increases above its accumulated costs, suggesting that over the longer-term this control strategy is profitable.

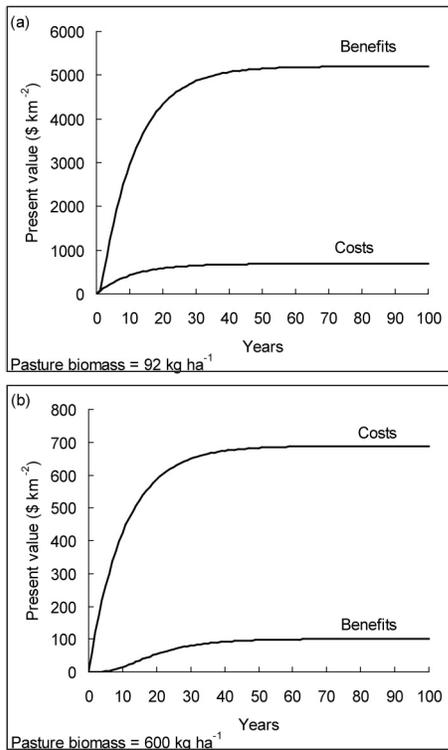
The need to aggregate benefits and costs through time introduces the complication that money earned or spent today is worth appreciably more than the same amount earned or spent at some point in the future. The value of a dollar currently in the hand declines into the future, because the potential to derive benefit from that dollar over the intervening period is a very real part of its current value. Ignoring inflation, the present value (*PV*) of money spent or additional income earned in the future is usually approximated as the dollar value of the amount (*D*), less the interest generated if that amount was invested now. Present value can be calculated from:

$$PV = \frac{D}{(1+i)^y} \quad (14)$$

where *i* is the annual interest rate that could be earned on the money if it was invested, and *y* is the number of years into the future that the additional income or expenditure is realized (Clark 1990). When used in this way, the interest rate is known as the discount

**Table 4.** Asymptotic present value of benefits and costs for helicopter shooting strategies employing an interval between operations of 1 to 5 years. The benefit/cost ratio of each strategy is also given, as well as the number of years after initial control that a profit from control was realized.

Interval between shooting operations (years)	Present value		Benefit/cost ratio	Years to achieve profit
	Asymptotic cost (A\$·km <sup>-2</sup> )	Asymptotic benefit (A\$·km <sup>-2</sup> )		
5	\$1,448	\$1,168	0.81	-
4	\$1,334	\$1,396	1.05	23
3	\$1,190	\$1,764	1.48	8
2	\$1,102	\$2,319	2.10	5
1	\$1,004	\$2,986	2.97	4

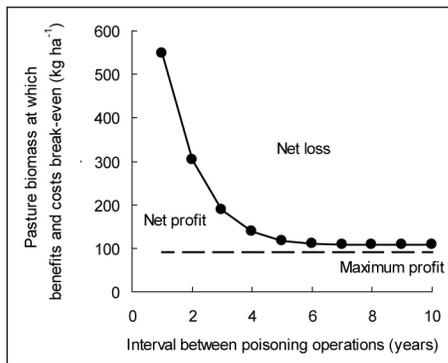


**Fig. 12. Variation in the present value of accumulated benefits and costs of annual 1080 poisoning to increase lamb production, with pasture biomass set to (a) 92 and (b) 600 kg·ha<sup>-1</sup>.**

rate. Where a sequence of expenses or earnings accrue through time, their present value is estimated from:

$$PV = \sum_{y=0}^Y \frac{D_y}{(1+i)^y} \tag{15}$$

where *Y* is the total number of years over which additional income and expenditure are accrued (Clark



**Fig. 13. The pasture biomass (kg·ha<sup>-1</sup>) at which the costs of poisoning at given intervals equate with benefits. The line splits the parameter space between pasture biomass and the frequency of poisoning into areas which will yield a net profit (below the line) and that which will yield a net less (above the line). The dashed line at the bottom of the figure indicates the pasture biomass at which the profitability of poisoning is always maximized (92 kg·ha<sup>-1</sup>).**

1990). Fig. 11c shows the cumulative costs and benefits of helicopter shooting summarized in Fig. 11b, corrected to their present values using an annual discount rate of 10%.

When costs and benefits are adjusted to their present value, the cumulative cost of undertaking helicopter shooting every 5 years always exceeds its benefits, and the strategy is not profitable. Details of the benefits and costs accruing for control strategies employing shorter intervals between helicopter shooting operations are summarized in Table 4. While all control strategies that employ intervals less than 5 years were profitable, the return on investment from control was highest where shooting was conducted annually. Annual shooting was most profitable because the present value of both the benefits and costs of control declined as the interval between shooting operations was reduced. While an increase in benefits at higher levels of control is intuitive (i.e., lower feral pig densities lead to higher lamb production), a decrease in costs is not. The accumulated costs of a helicopter shooting program will be the product of the number of shooting operations undertaken and the cost of each operation. While applying helicopter shooting less regularly means that the cost of fewer operations is incurred, the longer period pigs have to recover between operations means that the cost of each operation will increase. However, while pig density increases non-linearly until densities at *K* are approached, time accumulates only linearly. Hence, the rate at which program costs decrease as the frequency of operations declines is slower than the rate at which the cost of each control operation increases through the need to remove more pigs.

When helicopter shooting is replaced with 1080 poisoning, the influence of the relationship between prevailing pasture biomass and effectiveness on the benefits and costs of control must be considered, as well as that related to the frequency of its application. Fig. 12 shows variation in the present value of benefits and costs where 1080 poisoning is undertaken annually at a pasture biomass of 92 and 250 kg·ha<sup>-1</sup>. While the discounted costs of the 2 control programs are identical (A\$688.95·km<sup>-2</sup> over 100 years in present values), benefits are reduced at higher pasture biomass because poisoning operations are much less effective. Exploring the effect pasture biomass has on the benefits and costs of annual 1080 poisoning indicates a break-even point of 547 kg·ha<sup>-1</sup> above which control is not profitable. The break-even biomass declines as the interval between poisoning operations increases, defining a line that divides the parameter space between pasture biomass and the frequency of control into an area which results in net profit and an area that results in net loss (Fig. 13). The maximum profitability for each poisoning interval is maximized when pasture biomass is below 92 kg·ha<sup>-1</sup>, because most pigs will consume bait. By assuming

pasture biomass is always at this level, the maximum benefit/cost ratio could be calculated for poisoning applied at different intervals. For example, for annual poisoning, the maximum discounted benefit/cost ratio is 8.27, suggesting a much higher return on investment than that for helicopter shooting. However, because pasture biomass in the rangelands varies considerably from year-to-year, such an exercise is of dubious worth.

### Benefit/Cost Analysis Incorporating Stochastic Environmental Variation

Analyses based on simple population models such as the logistic allow the important influence that time has on the accumulation of benefits and costs for different pest control strategies to be analyzed. Strategies that appear profitable when considered as stand-alone activities may become unprofitable when considered in the context of longer-term changes in pest abundance. However, these simple models also have their limitations. For example, we know that rates of change in feral pig density are more systematically related to the availability of pasture than to their prevailing density (Choquenot 1998), and hence their recovery following control will not be as regular as that implied by the logistic model. We also know that because pasture biomass in the rangelands varies dramatically through time, its influence on the effectiveness of techniques like poisoning cannot be considered as constant over the course of a control program. Models that explicitly represent the trophic processes limiting pest density can lead to quite different interactions between control and pest abundance (Beddington and May 1977, Caughley and Gunn 1993, Choquenot 1998). Where trophic processes influence the effectiveness of specific control techniques, these models will also provide a more accurate picture of how control effectiveness varies with prevailing conditions.

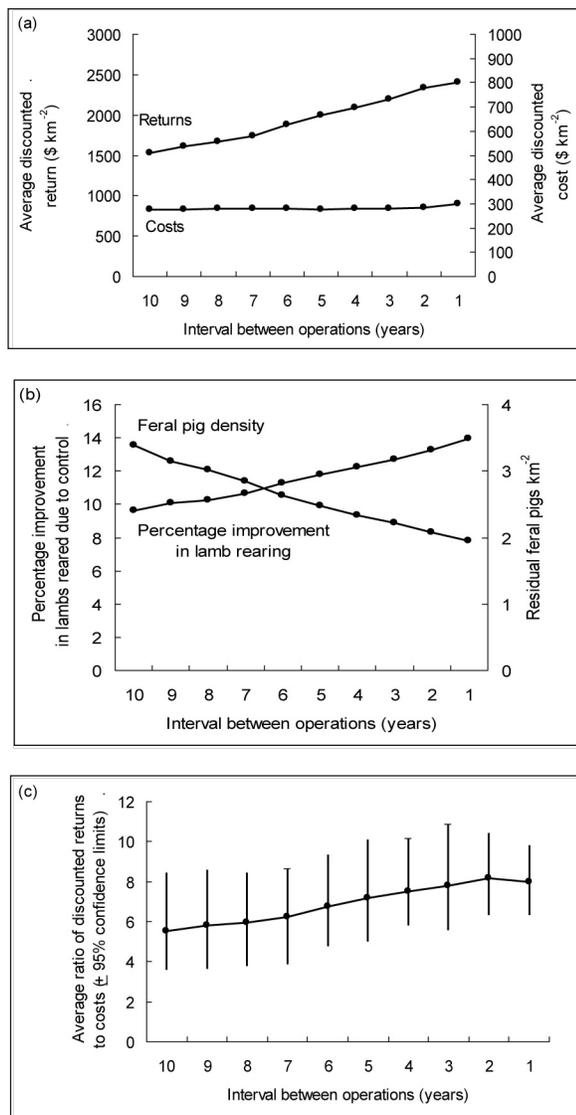
The interactive feral pig-pasture model described by equations 1 to 5 explicitly represents the effect that random variation in rainfall has on feral pig density in the rangelands through its influence on pasture availability. Using this model, the effect that given regimes of feral pig control have on their density and consequent variation in lamb production can be predicted more accurately than was possible with the logistic model used in the previous section. Moreover, because the interactive model also predicts variation in pasture biomass, it allows the influence that pasture availability has on the effectiveness of poisoning to be built into models used to compare control strategies.

In this section we replace the logistic model with the interactive model to explore how stochastic variation in rainfall, pasture growth and sources of lamb loss unrelated to predation by feral pigs, influence the benefits and cost of different pig control strategies. Because these models become complex, we will only describe

those developed for helicopter shooting. Incorporating realistic levels of environmental variation will have important consequences for the economic performance of pest control because nonlinearity in many of the functions that underpin trophic interaction means that increasing environmental variation often reduces average pest density (Caughley & Gunn 1993). Incorporating realistic amounts of variation into these models also allows uncertainty associated with returns on investment in pest control (i.e., investment risk) to be considered as part of their bioeconomic analysis (Clark 1990).

The model described in Fig. 2 was modified to simulate changes in feral pig density, pasture biomass and lamb production for 50 years, with pig control initiated in year 1. The annual time-step used in the logistic model was replaced with the weekly time-step used to account changes in pasture biomass and offtake. Costs and benefits of control were accumulated over the life of each simulation, with benefits estimated as the additional income produced in each year by feral pig control. To estimate the additional income accruing from feral pig control, two identical farming enterprises were modeled simultaneously, one for which feral pigs were controlled according to a prescribed regime, and the other where pigs were left uncontrolled. Lambing occurred in an 8-week season over the spring, with a realized rate of lamb predation estimated as a random draw from a truncated normal distribution (minimum and maximum values 0 and 1 respectively), with the average estimated from feral pig density using equation 7 and a standard deviation of  $\sigma = 0.031$ . For each simulation, the two enterprises received identical runs of 50 years rainfall. In each lambing season, any additional lambs produced by the enterprise where feral pigs were controlled were valued at A\$10, and attributed as a response to control. Ignoring instances where lamb production was lower for the enterprise where pigs were controlled truncates the potential benefits that can accrue from control at 0. All costs and benefits were discounted at an annual rate of 10% to convert them to present values.

To explore how the benefits and costs of helicopter shooting varied with the interval between shooting operations, the simulation model was iterated 5,000 times as this interval was decreased from 10 years to 1 year (i.e., the level of control was increased), and benefits and costs accruing from each interval control were accounted and compared. Variation in feral pig density unrelated to helicopter shooting meant that densities at the time a shooting operation was initiated were sometimes below the minimum required for shooting to remain profitable in the marginal analysis described above ( $1.5 \text{ pigs} \cdot \text{km}^{-2}$ ). However, because farmers did not know the density of feral pigs prior to commencing a shooting operation, they could only ascertain that there were too few pigs for shooting to be profitable after



**Fig. 14. Predicted variation in (a) the average discounted costs and returns (A\$.km<sup>-2</sup>), (b) average residual density of feral pigs (n.km<sup>-2</sup>), and associated changes in the percentage improvement in lamb rearing rates, and (c) the ratio of predicted variation in the average discounted costs to returns (both measured as A\$.km<sup>-2</sup>), and associated 95% confidence limits, as the interval between helicopter shooting operations for feral pigs is reduced from 10 years to 1 year. The improvement in lamb-rearing performance was the difference in the percentage of lambs born that were eaten by feral pigs for the enterprise where feral pigs were controlled, subtracted from the same percentage for the enterprise where no feral pig control was undertaken. Averages are from 5,000 iterations of each control interval, and confidence limits are bootstrapped estimates.**

some shooting had been attempted. Hence, we imposed a minimum cost of A\$5.44.km<sup>-2</sup> for every shooting operation, which represented 1 minute of searching.km<sup>-2</sup>.

Fig. 14a shows the average present value of accumulated costs and returns from helicopter shooting, as the interval between operations is reduced from 10 years to 1 year. Returns increased with the level

of control because average feral pig density declined, elevating lamb production (Fig. 14b). On average, residual feral pig density decreased by 16% for each incremental reduction in the interval between shooting operations, which led to a 0.43% increase in the percentage of lambs reared. In contrast to benefits of control, costs remained fairly constant, reflecting the trade-off between the frequency of shooting operations and recovery in feral pig density discussed in the previous section. However, where rates of change in feral pig density were driven purely by their density (i.e., the logistic model), this trade-off more than compensated for the lower frequencies of control, leading to increasing control costs as the overall level of control was reduced. The trade-off for the interactive model is not as strong because rates of change in feral pig density are driven by changes in pasture availability, through their effect on food intake. This has the effect of balancing reductions in control costs due to the lower frequency of shooting operations required, with the higher costs due to higher residual feral pig densities.

Over the range of shooting strategies that were simulated, the returns from helicopter shooting always exceeded its costs, indicating that helicopter shooting was always profitable. However, the average benefit/cost ratio increased with the frequency of helicopter shooting up to an interval of 2 years, suggesting that greatest profitability was achieved by initiating helicopter shooting every year or 2 (Fig. 14c).

The certainty associated with the average return on investment in helicopter shooting (indicated by the confidence limits around average benefit/cost ratios shown in Fig.14c), was low. For example, while the highest average return on investment for helicopter shooting was achieved by a 2-year interval between shooting operations (average benefit/cost ratio = 8.2), in 95 of 100 identical control programs the benefit/cost ratio could have been as low as 6.4 or as high as 10.4. It is important to note that this level of uncertainty was similar for all of the shooting strategies considered. Hence, the uncertainty associated with the benefits and costs of helicopter shooting reflects random variation in rainfall and pasture growth, and the effect factors unrelated to feral pig predation have on lamb production, rather than anything to do with the way shooting is implemented. The fact that uncertainty associated with returns is unrelated to the shooting strategy adopted means that while farmers should be aware of the risk that investment in helicopter shooting will realize lower than average returns, they cannot manage this risk by changing the frequency with which shooting is undertaken. Hence, once a farmer elects to initiate a helicopter shooting program, they should opt for more intense strategies as these will maximize the average return on investment, while accepting that the realized return may be higher or lower.

## DISCUSSION

### The Benefits and Costs of Feral Pig Control

Marginal analysis showed that reducing feral pig density to  $1.5 \cdot \text{km}^{-2}$  maximized the profit accruing from helicopter shooting through increased lamb production. If pasture biomass was above about  $220 \text{ kg} \cdot \text{ha}^{-1}$ , limitations on the effectiveness of 1080 poisoning meant that helicopter shooting was the more profitable control technique. However, as pasture biomass declined below  $220 \text{ kg} \cdot \text{ha}^{-1}$ , 1080 poisoning became progressively more profitable than helicopter shooting, attaining maximum profitability when pasture biomass was below  $92 \text{ kg} \cdot \text{ha}^{-1}$ . When a logistic model simulating density-dependent changes in feral pig population dynamics was added to benefit/cost analyses, the net benefit from helicopter shooting was maximized when it was applied annually (benefit/cost ratio = 2.97). While the potential net benefit from poisoning was also highest when it was applied annually (maximum potential benefit/cost ratio = 8.27), the realized net benefit was dependent on prevailing pasture biomass. When stochastic environmental variation was added to the model, the net benefit of helicopter shooting was still maximized by annual application. However, the average benefit/cost ratio increased to around 8 because the recovery in pig densities following shooting was moderated by prevailing pasture biomass. The net benefit of 1080 poisoning was maximized when free-feeding was initiated at low pasture biomass (less than  $100 \text{ kg} \cdot \text{ha}^{-1}$ ), and where poisoning followed free-feeding whenever some bait-take was evident. The resulting benefit/cost ratios averaged 35, indicating that this control strategy was potentially very profitable. However, the average benefit/cost ratio had a high degree of uncertainty associated with it, suggesting that while this control strategy was potentially profitable, there was considerable risk of achieving lower than expected net benefits. The increased costs required to modify the strategy to reduce uncertainty to levels that were comparable with helicopter shooting, reduced the average benefit/cost ratio to around 8, which was the same as that achieved by helicopter shooting.

While the model that included stochastic environmental variation comes close to representing the real dynamics of this management system, it makes several simplifying assumptions about how control, feral pig density and lamb production interact. Two assumptions which may be particularly important are that (1) there is no compensatory increase in the survival of lambs not eaten by feral pigs (Krebs 1994), and (2) pasture biomass has no direct effect on either sheep stocking rates or lamb survival independent of predation by feral pigs. Residual variation in the index of lamb loss estimated by Choquenot et al. (1997) would probably have included any compensatory survival among lambs as it

was estimated under field conditions. Hence, it is likely that predation rates estimated from equation 7 and their associated stochastic variation estimated from equation 8, will encompass compensatory increases in lamb survival when predation by feral pigs is high. However, the assumption that pasture availability has no effect on sheep stocking rates or the rate at which sheep produce lambs is more problematic. Unfortunately, while both the survival of sheep and their propensity to produce lambs under rangelands conditions is known to be affected by pasture availability (Kilgour 1992), there are no good data that would allow these effects to be built into the models described here. The net effect of ignoring the influence pasture availability has on the base production of lambs will exaggerate the potential that feral pig control has to generate profit under conditions of low pasture availability. Hence, the benefit/cost ratios estimated above should be considered a relative measure of the potential profitability of feral pig control, rather than as absolute values.

### Realism, Data, and the Specificity of Information Obtained

Bioeconomic analysis of pest management is based on models that predict how pest density and the resources pests affect respond to different strategies for pest control. Various analytical techniques can be applied to these models in order to draw useful information about pest management from them. The usefulness of this information will be limited by the realism of the underlying bioeconomic model. For example, the immediate benefits and costs of helicopter shooting and 1080 poisoning were contrasted by applying simple benefit/cost analyses to a model that required 3 and 5 parameters to describe the cost-effectiveness of helicopter shooting and 1080 poisoning respectively, and another 4 to describe the difference in lamb production with and without pig control. However, while this analysis was useful where a single control initiative was considered, it was not particularly useful where a program of control operations was likely to follow this initiative. Given that feral pig control is rarely contemplated as a single initiative commitment, neither the model used to assess alternative strategies for pig control nor the questions it was able to address were particularly realistic or useful.

Time was introduced to the analysis by using a simple model of pig population growth, and accounting the benefits and costs of control as present values. These two additions required a further 3 parameters to be estimated for the bioeconomic model, and the analysis to be expanded to represent the effects of time on how benefits and costs accumulated. The more complex analysis remained focused on the same question (identifying the most profitable control strategies

for feral pigs), however its realism had been increased by considering how the benefits and costs of alternative strategies for pig control accumulate through time. The information gleaned would be useful to people interested in the general performance of different control techniques for improving the economic viability of wool-growing enterprises. However, the simple population models used in the analysis could not simulate the effect that stochastic environmental effects would have on the effectiveness of feral pig control, or on the response of pig populations and lamb production to the level of control imposed. These limitations constrain the capacity of simple models to consider the important influence that uncertainty has on the way the benefits and costs of feral pig control accrue. As such, the information provided by the analysis would be of limited use to people who require assistance in making year-to-year decisions about how to impose feral pig control.

These short-comings were addressed by replacing the logistic model of pig population dynamics with a model that explicitly represented interaction between feral pigs, their pasture resources, and the other herbivores with whom they shared these resources. The addition of this more complex model allowed the effect of stochastic variation in rainfall and pasture growth on fluctuations in uncontrolled feral pig density to be simulated. Stochastic variation in lamb predation rates was also included in the model, allowing uncertainty associated with production responses to feral pig control to be considered explicitly. Incorporating this added realism into the underlying bioeconomic model, allowed uncertainty and the attitude of individual farmers to risk to be built in to the analysis of benefits and costs accruing from alternative feral pig control strategies. However, the more complex nature of the model required 15 additional parameters to be estimated.

When the 3 analyses of feral pig control are compared, the specificity of management information that each provides increases in parallel with the realism of the underlying bioeconomic model. The first 2 analyses based on fairly abstract models of feral pig control, provide useful general information on the relative profitability of helicopter shooting and 1080 poisoning. In contrast, the third analysis based on a much more realistic model of feral pig control provides highly prescriptive information on how the profitability of these control techniques could be maximized. However, the number of parameters necessary to improve the level of realism in these models increased dramatically, suggesting that the amount of data required to estimate bioeconomic models grows exponentially with their degree of realism. Given the cost of undertaking robust research into many pest management systems, this rapid increase in data requirements has important implications for how bioeconomic modeling is applied to improve pest management decisions.

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